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Pressure-sensitive Bio-compatible Skin Sleeve for Millimetre-Scale Flexible Instruments

P. Wasylczyk[1*], F. Ozimek[2], M. Tiwari[1,3], L. Da Cruz[1,4], C. Bergeles[1]

[1]Wellcome/EPSRC Centre for Interventional and Surgical Sciences, UCL, UK

[2]Mullard Space Science Laboratory, UCL, UK

[3]Nanoengineered Systems Laboratory, UCL Mechanical Engineering, UCL, UK

[4]Moorfields Eye Hospital, UK

*p.wasylczyk@ucl.ac.uk

INTRODUCTION

During robot-assisted medical interventions robotic arms, tools and end effectors usually encounter contact forces from the surrounding tissues. While most procedures rely on images for guiding the tools, tactile feedback could provide valuable complementary information. Figure 1a shows an illustration of a 5 mm diameter flexible robotic arm, covered with a flexible skin comprising tens of tactile elements (tactels) functioning as pressure sensors. The tactels are connected via an array of electrodes that read out the external forces exerted on the robot on its way to the operating area inside the body. We have developed such flexible skin with piezoresistive pressure sensors, that may cover a robotic arm or other tools (such as endoscope probes) and provide continuous information on these reactive forces (Fig. 1b).

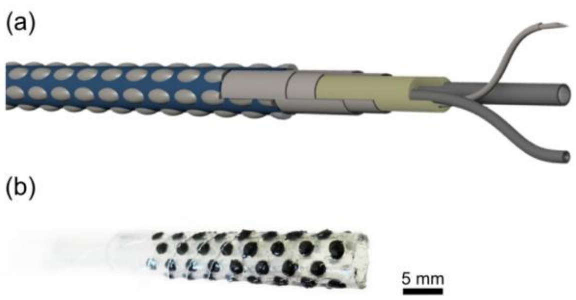

Fig. 1 Tubular pressure-sensitive soft sensor skin. (a) Illustration of a concentric tube soft robotic arm covered with a pressure sensor array. **(b)** Prototype sensor with 8×8 tactile pixel array and wire electrodes embedded in a soft silicone rubber carrier membrane; the outer diameter is 7 mm.

MATERIALS AND METHODS

Flexible pressure sensors use a grid of capacitance [1], piezoelectric [2] or piezoresistive [3] elements to measure the distribution of external forces. Piezoresistive sensors usually rely on arrays of tactels embedded on or within a soft carrier membrane. Most of the devices demonstrated to date have planar geometry and tens to hundreds of tactels on a millimetre-spaced grid. The tactels are most often made of a soft material (such as carbon-loaded silicone rubber) [4, 5] or micro-channels filled with eGaIn – a metal alloy that remains liquid at room (and body) temperature [6]. The membranes are typically made of soft silicone rubber or polyimide films with the electrodes in the form of printed paths (e.g. screen-printed with silver-loaded ink) or embedded metal wires. While eGain may offer sophisticated sensing geometries (such as measuring pressure and shear forces with the same tactel), it is unlikely to be approved for medical use inside the body. Silicone rubbers, on the contrary, are bio-compatible and, in combination with suitable carbon compounds, can be the material of choice for sensing elements in medical applications.

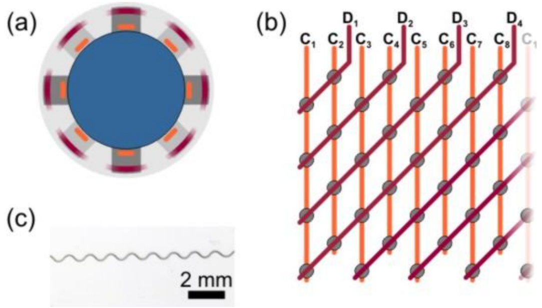

Fig. 2 Pressure-sensitive sensor design. (a) Cross section of a robot or instrument arm (blue) covered with the soft silicone membrane (light gray). Embedded in the membrane are tactile pixels (tactels, dark grey) and two layers of wire electrodes – bottom, column electrodes (orange) and top, diagonal ones (purple). **(b)** Electrode layout (shown on a plane) with 8 column ($C_{1\text{-}8}$) and four diagonal ($D_{1\text{-}4}$) electrodes. **(c)** Photograph of the undulating wire used for the electrodes.

Figure 2a presents the cross section of the sensitive skin sleeve on a cylindrical instrument. The 1 mm thick carrier membrane is cast in a two-part poly(methyl methacrylate) **(**PMMA) mould from soft silicone rubber (Gumosil AD-1, Silikony Polskie, 30°Sh A, 650% elongation at break) in the form of a tube – its 5 mm inner diameter matches the instrument size. The electrode array, with the layout sketched in Fig. 2b, is made of silver-plated copper wire (Scientific Wire Company, 0.1 mm diameter). As a straight wire mesh embedded in the silicone tube would significantly reduce the soft skin flexibility, the wire has been processed to make an undulating shape with 0.6 mm width and 0.8 mm period (Fig. 2c). This allows the electrode to follow the membrane expansion, as the flexible instrument bends. Each of 32 tactels is a 1.4 mm cylinder made of carbon-loaded silicone (AD-1 with 10% w/w carbon black, Super P, Conductive, H30253, Alfa Aesar) with a bottom and top electrodes. The tactels are made by injecting the carbon-loaded silicone into cavities laser-milled in the silicone membrane. The resistance of an individual tactel measured between the bottom and top wire electrodes with no force applied is 0.5±0.1 kΩ.

The two-dimensional tactel array is read out with a set of column and diagonal electrodes [7, 8]. Eight column electrodes are addressed one by one in sequence via a multiplexer, and in every cycle the voltage on the four diagonal electrodes is measured. The multiplexer (MUX, DG509, Maxim) is driven with digital outputs of a USB DAQ card (USB-1608G, Measurement Computing) and the same card's four analog inputs sequentially read out the diagonal electrode potentials. As such electrode arrangement suffers from the crosstalk between tactels, a virtual ground technique with high-gain op-amps (TL084, Texas Instruments) [9] is used (Fig. 3a). Data acquisition, processing and visualisation is performed in LabView.

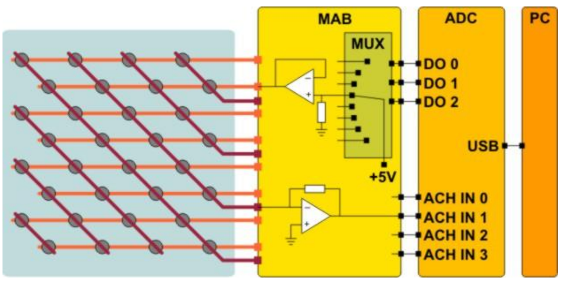

Fig. 3 Sensor array readout electronics. MAB - multiplexer and op-amp board, ADC – analog and digital I/O card, DO 0-2 – digital outputs, ACH IN 1-4 – analog inputs, PC - personal computer. For clarity only one addressing line (out of 8) and one readout channel (out of 4) are shown.

RESULTS

Figure 4a presents the normalized, background-subtracted response of a single tactel, measured with a digital balance. The useful pressure range extends to around 400 kPa (assuming uniform load onto the tactel area), above which the sensor saturates. Measured single tactel transient response to an impulsive load in Fig. 4b shows rise and fall times of around 50 ms. Figure 4c shows the 4×8 sensor array readout in the LabView front panel with 620 kPa pressure applied to one tactel.

DISCUSSION

A flexible, soft pressure sensing sleeve using only medical grade materials was designed, built and characterized. With similar technologies the sensor can be scaled down to cover 1-2 mm diameter tools and smaller with silicone 3D printing. The parameters to be optimised are the tactel diameter, thickness and material. Uniformity of the tactels within the sensor, tactel-electrode contact as well as the readout noise and signal processing are also to be further researched.

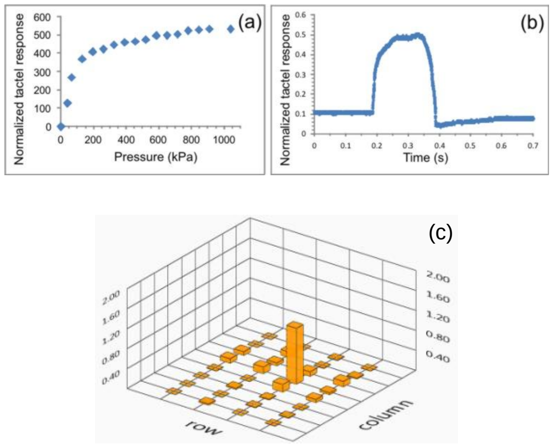

Fig. 4 Pressure sensor response. (a) Measured response of a single tactel to the applied pressure. **(b)** Measured transient response of a single tactel to an impulsive load. The horizontal scale spans 700 ms, the rise and fall times are around 50 ms. **(c)** Snapshot of the 4×8 sensor array readout with 620 kPa pressure applied one tactel (assuming even load distribution over the tactel area, with the background signal subtracted).

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